Light Emitting Diodes and Lasers for High-Speed Underwater Optical Communications

Georgios N. Arvanitakis[1,2], Jonathan J. D. McKendry[1], Henry T. Bookey[2], Erdan Gu[1], and Martin D. Dawson[1,2]

1: Institute of Photonics, Department of Physics, University of Strathclyde, G1 1RD, Glasgow-Scotland
2: Fraunhofer Centre for Applied Photonics, G1 1RD, Glasgow-Scotland

1 Introduction

During the last decade, a lot of research has been carried-out around Underwater Wireless Optical Communications (UWOC) as they are considered as a promising technology for high data rate transmission in underwater environments. The main application domains that require Underwater Wireless Communications include[1]:

a) The military: for tactical surveillance and communications between e.g. submarines and surface vessels.
b) Industry: e.g. for oil and gas control maintenance, underwater construction and subsea factories.
c) The scientific community: e.g. for offshore explorations and oceanography research, pollution and climate change monitoring.

All the above activities require the deployment of sophisticated sensors and other subsea devices, such as unmanned (UUVs) and autonomous underwater vehicles (AUVs), therefore the amount of data to be transmitted and the accompanying data rates continue to rise. While data links can be achieved using underwater cables or tethers, this can be very restrictive, expensive or in some cases impractical. Therefore, underwater wireless links are greatly desirable. Underwater wireless data communications require also an environment that will support propagation of the carrier wave with low enough attenuation and background noise.

UWOC are being considered for use underwater as water exhibits a window of reduced attenuation in the visible spectrum, particularly between $400 - 550nm$[2]. Thus, as RF signals require large antennas size, suffer from high attenuation in sea water and acoustic can provide data rate of few kb/s, the employment of light sources, such as diode lasers and GaN-based LEDs, operating in the blue-green region enable one to exceed Gb/s (e.g. $12.4Gb/s$ for $1.7m$ of tap water at $450nm$ via a GaN laser diode[3]) at a distance of tens of meters (e.g. $1.2Mb/s$ for $30m$ in a pool via 6 LEDs array at $420nm$[4]) due to high frequency of optical carrier. Also, they require low operating power i.e. few Watts whilst acoustic requires tens of Watts and RF tens up to hundreds of Watts, depending on the transmission distance[1]. To summarize the characteristics of the above-mentioned technologies that govern Underwater Wireless Communications, a table is given below (Table 1-1)[1].

PARAMETERS	ACOUSTIC	RF	OPTICAL
Attenuation	$0.1-4dB/km$	$3.5-5dB/m$	$0.39dB/m$ (clear ocean) $-11dB/m$ (turbid)
Speed	$1500m/s$	$\approx 2.55\times10^8m/s$	$\approx 2.55\times10^8m/s$
Data rate	$\sim kb/s$	$\sim Mb/s$	$\sim Gb/s$
Distance	Up to kms	Up to $\approx 10m$	$\approx 10-100m$
Frequency band	$10-15kHz$	$30-300Hz$ (ELF)	$10^{12}-10^{15}Hz$
Transmission power	Tens of $Watts$	Few mW to hundreds of $Watts$	Few $Watts$
Antenna size	$0.1m$	$0.5m$	$0.1m$
Performance parameter	Temperature, salinity, pressure	Conductivity and permittivity	Absorption, Scattering

Table 1-1Comparison of the three dominant Underwater Wireless Communications Technologies

However, applying UWOC is not a trivial matter due to absorption and scattering effects produced by the molecular structure of water[5] and from substances contained within sea water such as dissolved organic materials with a diameter $< 0.4\mu m$[6] (gelbstoff), particulate organic materials (phytoplankton) and suspended inorganic particles (rocks, sands, clays)[7]. In general, the existence of these materials results in shifting and narrowing of the low attenuation region from the blue-green towards longer wavelengths[2,5,7], as the concentration increases.

While UWOC links have been widely reported in the literature, for example $5.5Gb/s$ using a green Laser diode at $520nm$ over a $5m$ air channel and a $21m$ water channel[8], these are typically “point to point” links, where a single transmitter (T_x) addresses a single receiver (R_x). This requires optical alignment to be maintained between T_x and R_x, which may be challenging in open waters. As such, in this paper we report the employment of the Corning® Fibrance® Light Diffusing Fiber[9,10] as a transmitter (T_x). This thin, flexible optical fiber, made from glass, exhibits the property of scattering light for lighting purposes instead of delivering it from point to point over long distances. Its silica core is doped with scattering centers to scatter light continuously and uniformly along the length of the fiber.

In this way a simple and cost-effective omnidirectional "beacon" is realized with no moving or complex optical parts nor precise alignment despite the challenging underwater environment. This omnidirectional beacon could be used to establish a wireless data link within a volume of water, such as a ship broadcasting to multiple divers or, remotely-operated vehicles (ROVS) etc. that are in proximity to the ship. Another scenario could be that an ROV uses the beacon concept to communicate to a surface vessel, without the requirement to continuously track and optically align the data link. As discussed previously, optical wireless data links can remove the need for tethered communications, greatly increasing mobility, functionality and reducing costs.

2 Description of the Experimental Set-Up

The lab-based experimental set-up implemented in our work to date, may be seen in Figure 2.1.

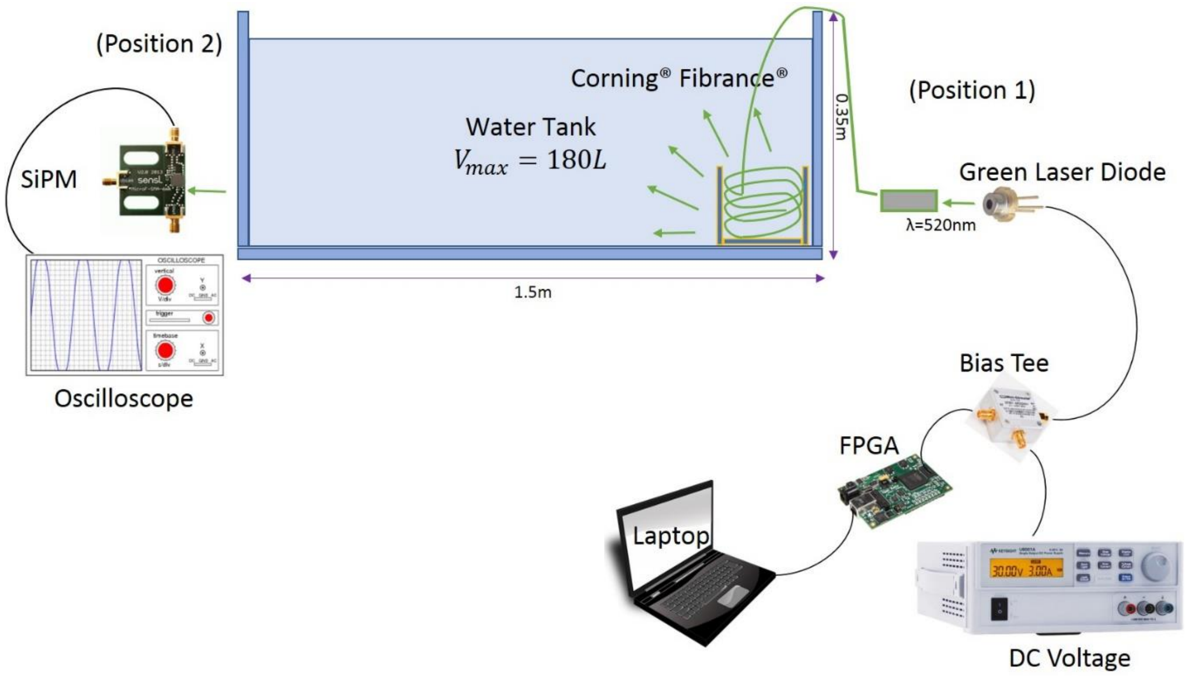

Figure 2.1 Schematic of the lab-based experimental set-up

As previously mentioned, it consists of a transmitter (T_x) which is the Corning® Fibrance® Light Diffusing Fiber, $5m$ long, positioned inside a glass beaker (see Figure 2.2a).

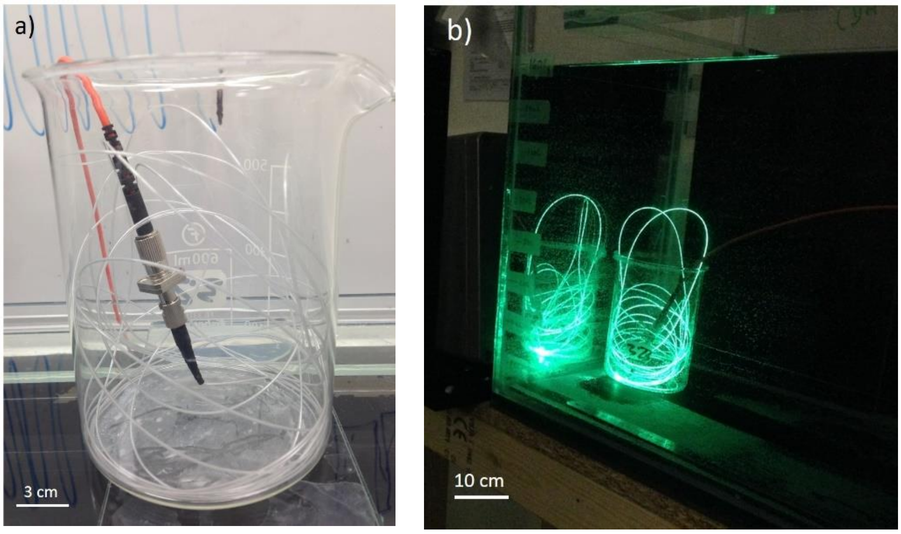

Figure 2.2 a) Photograph of the Fibrance inside the beaker and b) photograph of the Fibrance transmitter, coupled with the green Laser Diode and acting as Transmitter, inside the water tank, filled with clear tap water

The Fibrance was coupled with an off-the-shelf Osram Green Laser Diode (model PL520) operated at $520nm$ (Figure 2.2b), supplied by a current of $90mA$ and a forward Voltage of $6.5V$ from a single output DC power supply. The transmitted power of the beam was $\sim 5mW$, measured by a THORLABS PM100A Power Meter with a S121C sensor head.

The On-Off Keying (OOK) modulation scheme was used for generating a Pseudo Random Bit Sequence (PRBS) of 127 bits via an Opal Kelly XEM3010 FPGA. The FPGA data output and the DC supply were combined and used to drive the laser diode using a bias tee. The FPGA was run by a MATLAB® script through a laptop.

The beaker containing the Fibrance transmitter fibre, was placed at the bottom of the water tank of dimensions $1.5m \times 0.35m \times 0.35m$ and maximum volume of $180l$ (see Figure 2.3). The tank was constructed from high transmittance[11] (91%) Pilkington Optiwhite™ aquarium glass to reduce optical losses. The tank was filled with $160l$ of tap water. Moreover, to prevent reflections coming from the walls of the tank which would not occur in open water and may lead to multipath signal distortions, matt black plastic sheets were placed at the bottom of the tank and around the walls.

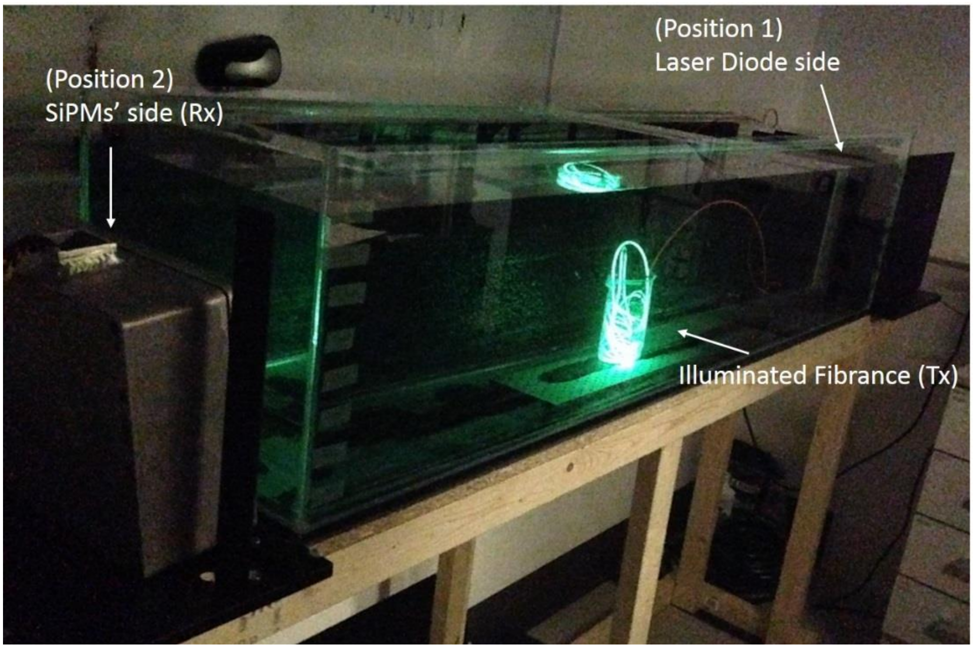

Figure 2.3 Photograph of the water tank filled with $140l$ *of clear tap water and the Fibrance transmitter inside the beaker and placed on the bottom of the tank*

As for the detector (R_x), a $6 \times 6mm^2$ SensL J-series 60035 Silicon Photomultiplier (SiPM) is placed at the other side of the tank (Position 2 in Figure 2.3), approximately aligned with the Fibrance transmitter and sufficient enough to collect part of the signal propagated through water, either scattered due to Maalox® (our scattering agent) or not. The SiPM, was connected to an oscilloscope for monitoring and analysing the signal.

As previously mentioned, the propagation of an optical beam underwater suffers from loss of intensity with distance due to absorption and scattering.

The optical properties of ocean water are defined by parameters such as the attenuation coefficient (c in m^{-1}) and the single scattering albedo, ω_0.

The attenuation coefficient describes the differential power loss per unit volume of water caused by absorption and scattering and is the sum of both the absorption α, and scattering b, coefficients ($c(\lambda) = a(\lambda) + b(\lambda)$). It varies greatly according to the water type and is also wavelength dependent. Some typical values of the coefficients can be seen in the following table (Table 2-1), in addition to the optimum operating wavelengths for different types of water.

The scattering albedo is defined as the ratio between the amount of scattering and overall attenuation, or $\omega_0 = b/c$. Natural waters have single scattering albedos that range from 0.25 to > 0.8 as the water becomes scattering[12].

Water type	$a(m^{-1})$	$b(m^{-1})$	$c(m^{-1})$	Operating Wavelength
Clear Ocean	0.114	0.037	0.151	$450 - 500nm$ (blue-green)
Coastal Ocean	0.179	0.220	0.339	$520 - 570nm$ (yellow-green)
Turbid Harbour	0.366	1.829	2.195	$550 - 600nm$ (yellow-green)

Table 2-1 Typical values of absorption, scattering and attenuation coefficients and ideal transmission wavelength for different types of water.[1]

In general, underwater optical propagation experiments are commonly done with simulated conditions in a laboratory water tank. In order to mimic the conditions found in natural waters, different concentrations of a scattering agent are diluted in tap water. As a scattering agent, Maalox® antacid, a mix of magnesium hydroxide ($Mg(OH)_2$) and aluminium hydroxide ($Al(OH)_3$), was used here. It has an albedo of $\omega_{0,Maalox®} = 0.95$[13–15].

The received power, P_R, can be found by applying the Beer's Law over a path d (Eq. 1), giving us a basic solution to the problem of determining the loss of light along a path in ocean water[12].

$$P_R = P_0 e^{-cd} \qquad \text{(Eq. 1)}$$

Also, it is worth mentioning that we can define the attenuation length, d_{atten}, as being the distance at which P_R has fallen to $1/e$ of P_0. Thus, $d_{atten} = {}^{1}/_{c}$ while the product cd_{atten} forms a unitless term which represents the number of attenuation lengths (AL)[12].

3 Results

The main purpose of the experiment was to implement the beacon in an underwater environment and show that a data rates up to $5Mb/s$ is achievable through different types of water, thus, different Maalox® concentrations in water.

The maximum distance between transmitter and receiver, was $1.66m$ ($1.5m$ through water). The $0\ to\ 3.3V$ digital Pseudo-Random Bit Sequence (PRBS) signal that was sent to the Laser Diode and was optically transmitted through water, had the form as shown in Figure 3.1. The PRBS is 127 bits long and was transmitted at a fixed data rate of $5Mb/s$.

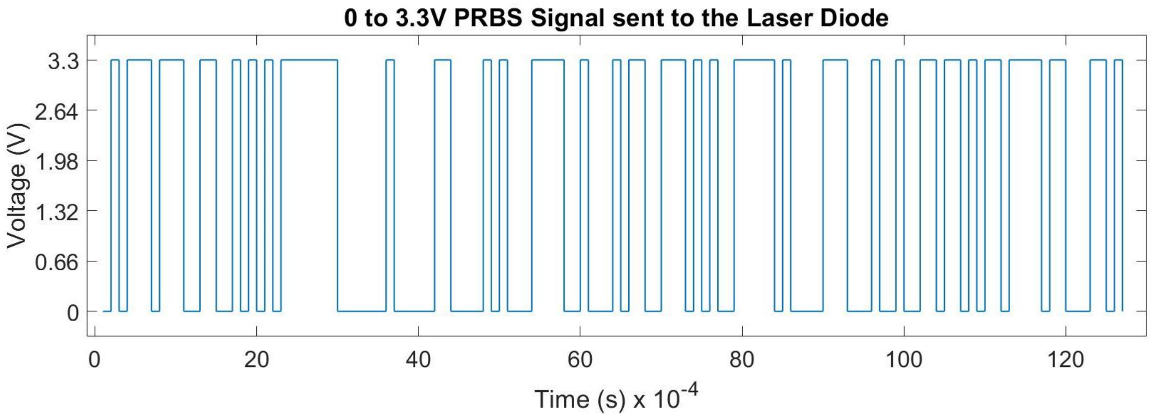

Figure 3.1 The form of the 0 to 3.3V PRBS signal that was optically transmitted through water

Different concentrations of Maalox® were tested in order to mimic three typical types of sea water (see Figure 3.2 - Figure 3.4) whose attenuation coefficients and attenuation lengths are known (see Table 2-1). As it can be seen, the underwater link based on the Fibrance transmitter, could distinctly support the $5Mb/s$ optical signal in all types of natural water analogues, for a given distance of $1.66m$ between transmitter and receiver which was the maximum we could set with the current set-up layout. The following graphs of the received signal present great similarity to the digital signal in Figure 3.1 and any possible distortion coming from ambient noise is negligible.

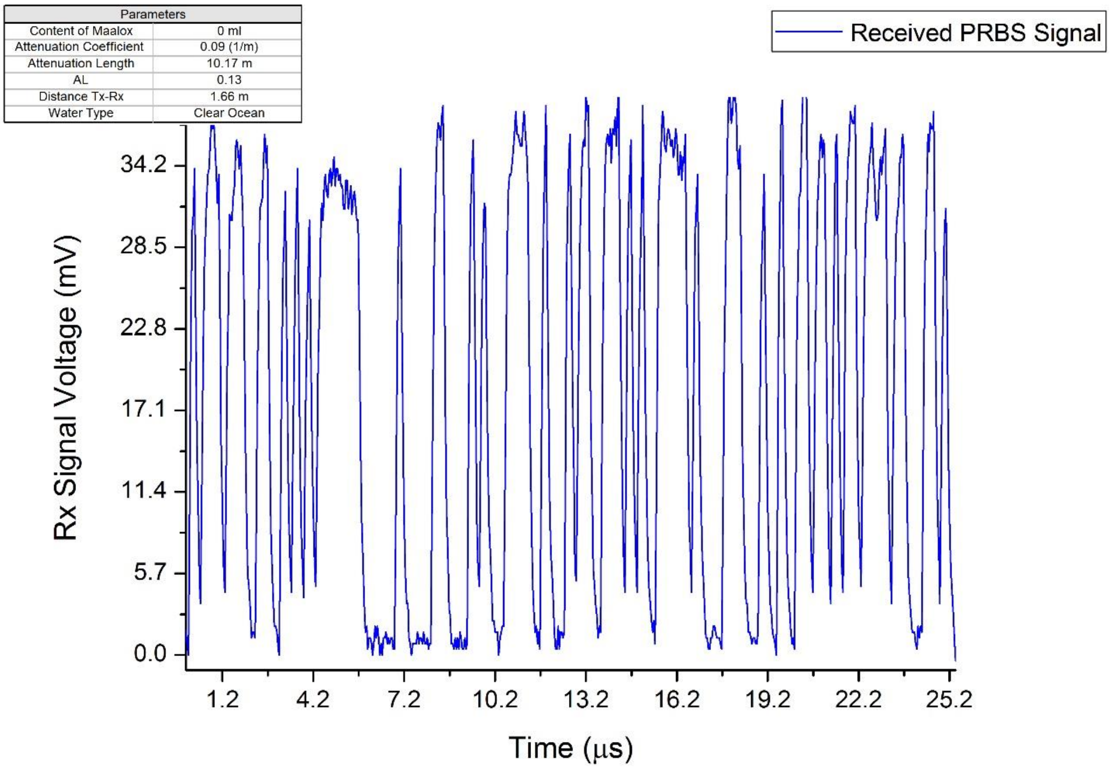

Figure 3.2 Graph of the received signal for "Clear Ocean" water and $d_{Tx-Rx} = 1.66m$

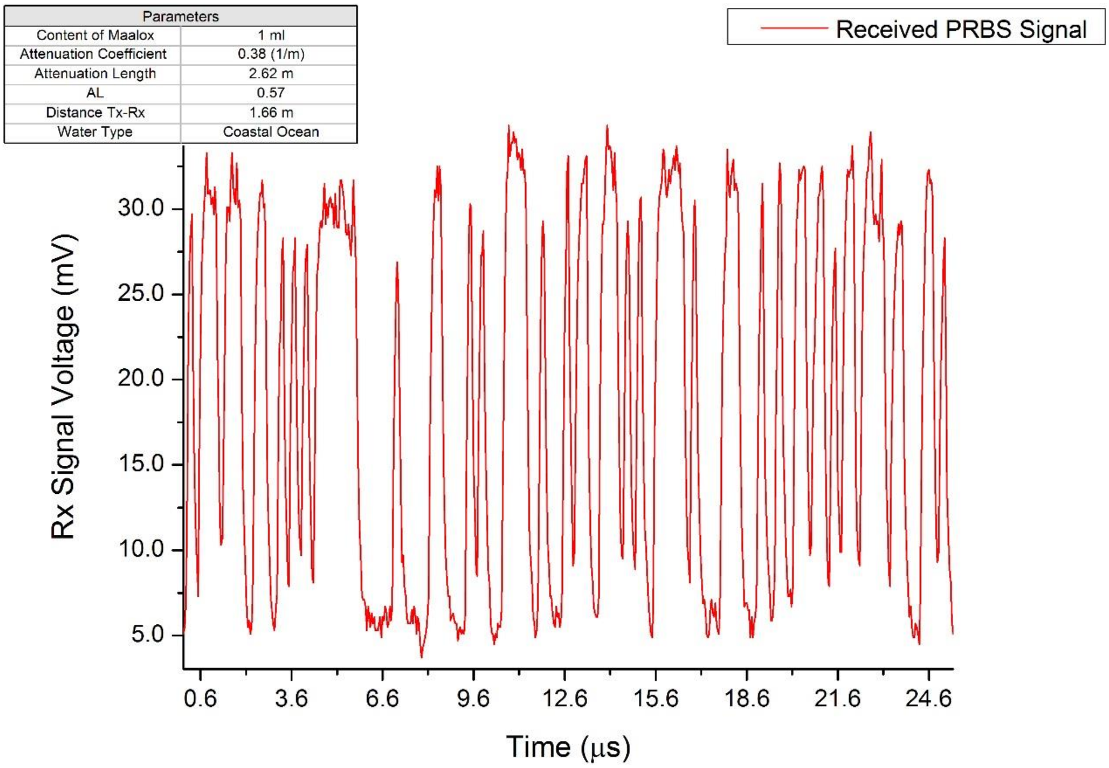

Figure 3.3 Graph of the received signal for "Coastal Ocean" water and $d_{Tx-Rx} = 1.66m$

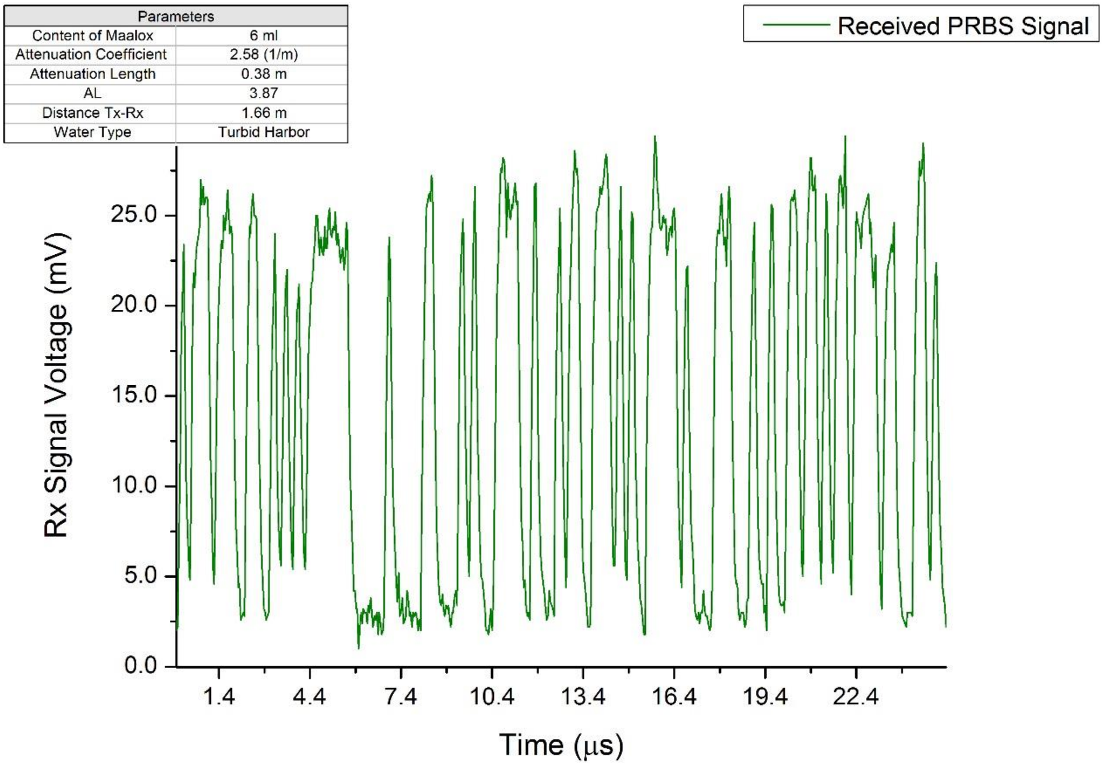

Figure 3.4 Graph of the received signal for "Turbid Harbor" water and $d_{Tx-Rx} = 1.66m$

Moreover, the turbidity of the water was expanded in more extreme levels so as to acquire an estimation about the supporting limit of the set-up.

Three higher concentrations of Maalox® were tested, $18ml$ (0.0125%), $28ml$ (0.0175%), and $40ml$ (0.025%) whose attenuation lengths correspond to few centimetres. The distance between T_x and R_x remained constant $(1.66m)$, however for the $40ml$ of the scattering agent two positions of the Fibrance transmitter were checked; for the closer distance to the SiPM $(0.75m)$ the signal was clearer.

The results can be seen in Figure 3.5 - Figure 3.8. The transmittance of $5Mb/s$ of optical signal in a very turbid underwater environment was achieved.

These results, enable us to confirm the efficiency and cost/power-effectiveness of the Fibrance transmitter. It could be now deduced that the Fibrance concept would be rendered robust enough for the "real world" applications discussed in the Introduction section.

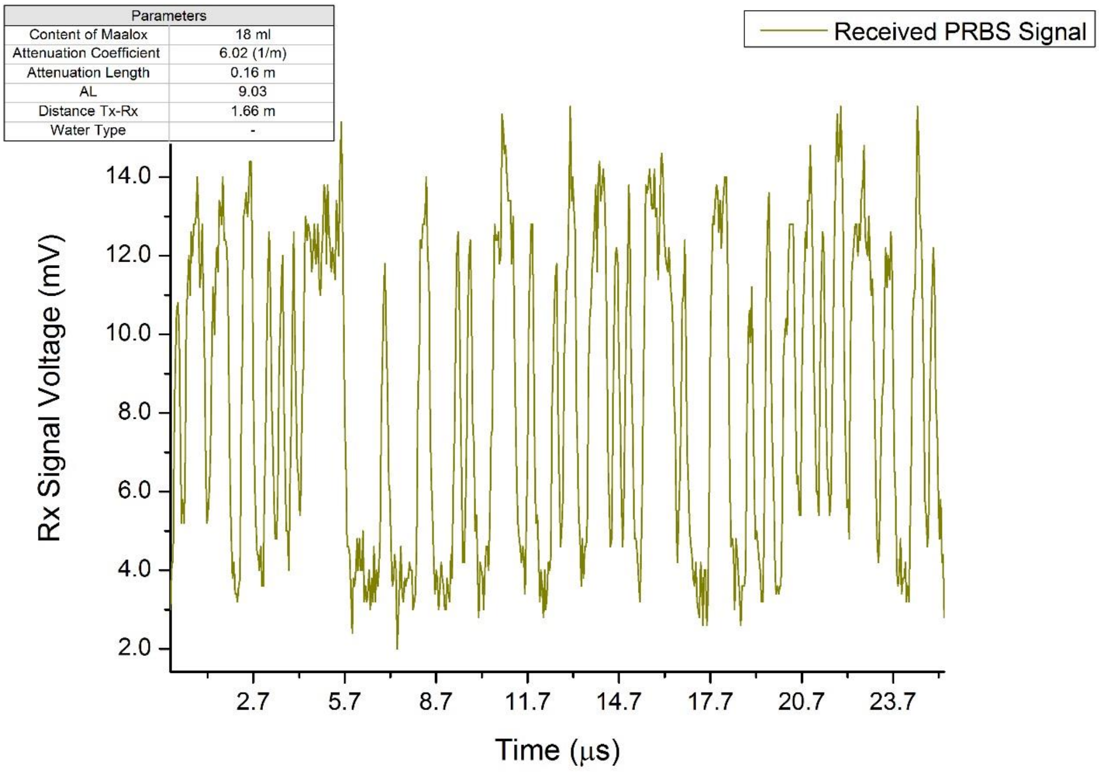

Figure 3.5 Graph of the received signal for an attenuation length of $0.16m$ *and* $d_{Tx-Rx} = 1.66m$

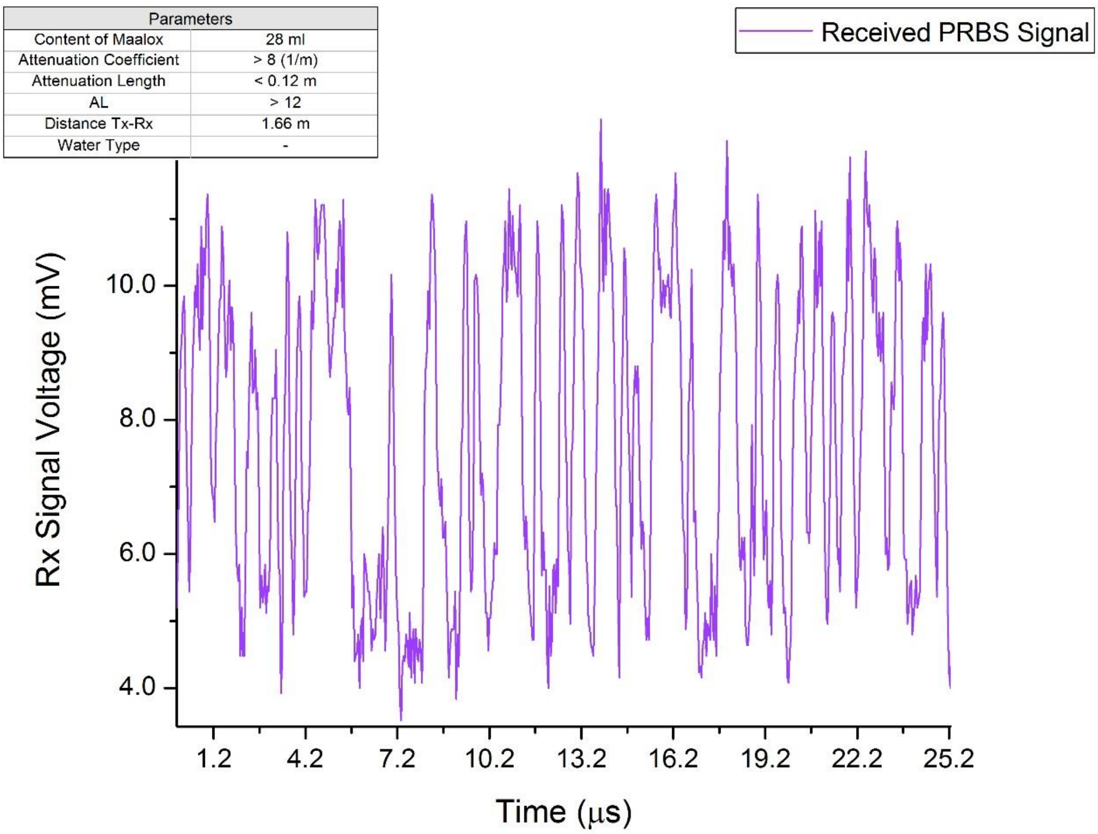

Figure 3.6 Graph of the received signal for an attenuation length smaller than $0.12m$ *and* $d_{Tx-Rx} = 1.66m$

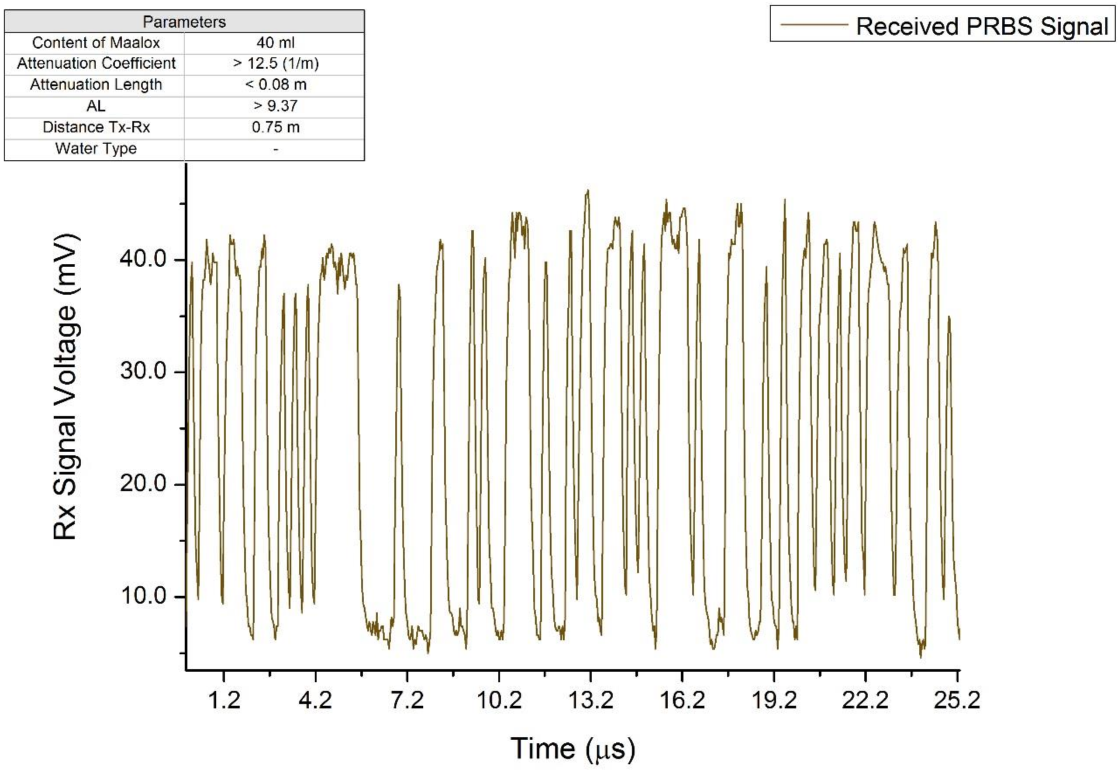

Figure 3.7 Graph of the received signal for an attenuation length smaller than 0.08m and $d_{Tx-Rx} = 0.75m$

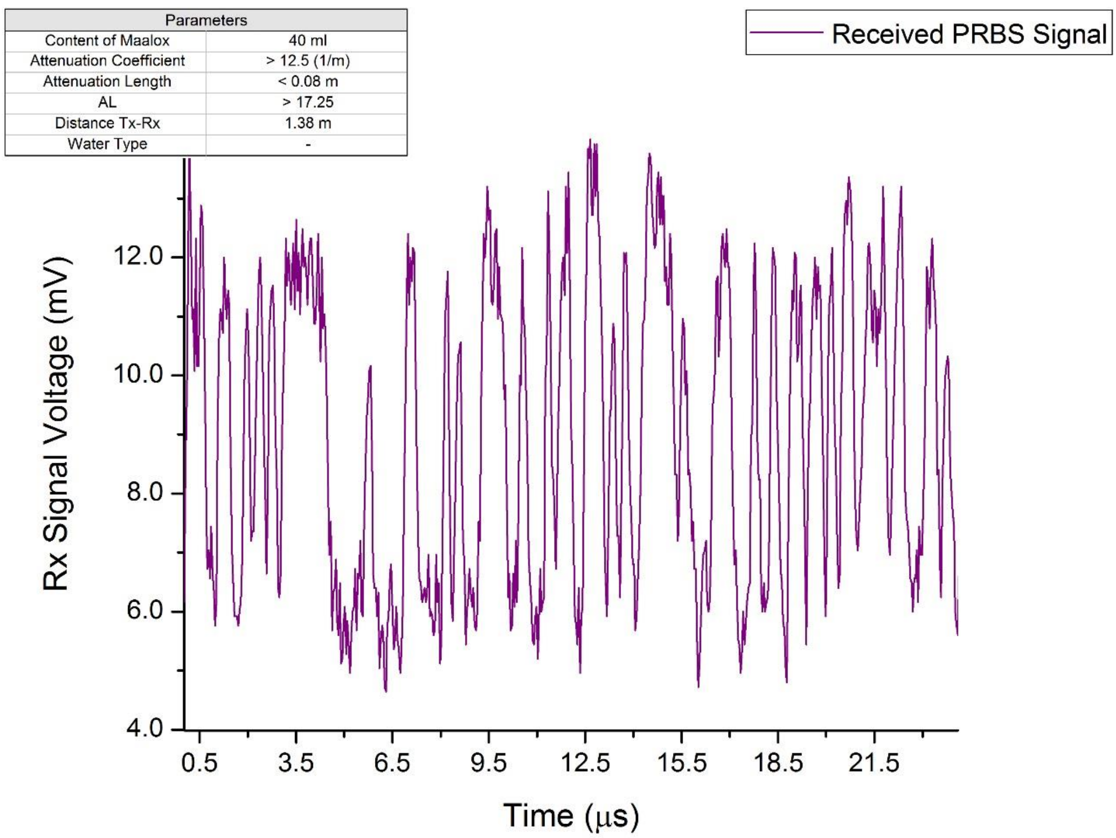

Figure 3.8 Graph of the received signal for an attenuation length smaller than $0.08m$ *and* $d_{Tx-Rx} = 1.66m$

Regarding the distances that could be supported with the current configuration outside of the water tank, in Figure 3.9 an estimated BER versus transmission distance (the distance between the T_x and R_x) was plotted for the three types of natural waters (Clear Ocean, Coastal Ocean and Turbid Harbor) with corresponding attenuation coefficients given in Table 2-1. These results have been calculated using the methodology given by Hamza T. et al.[16], adapting the calculations such that it is assumed that the Fibrance transmitter is an isotropic emitter, emitting power equally in all directions, rather than for example a Lambertian emitter. $5mW$ of transmitted optical power, at a wavelength of $520nm$ is assumed, and the specifications of the SiPM used in our experiments is used as the receiver. Data is assumed to be transmitted at 5 Mb/s using OOK.

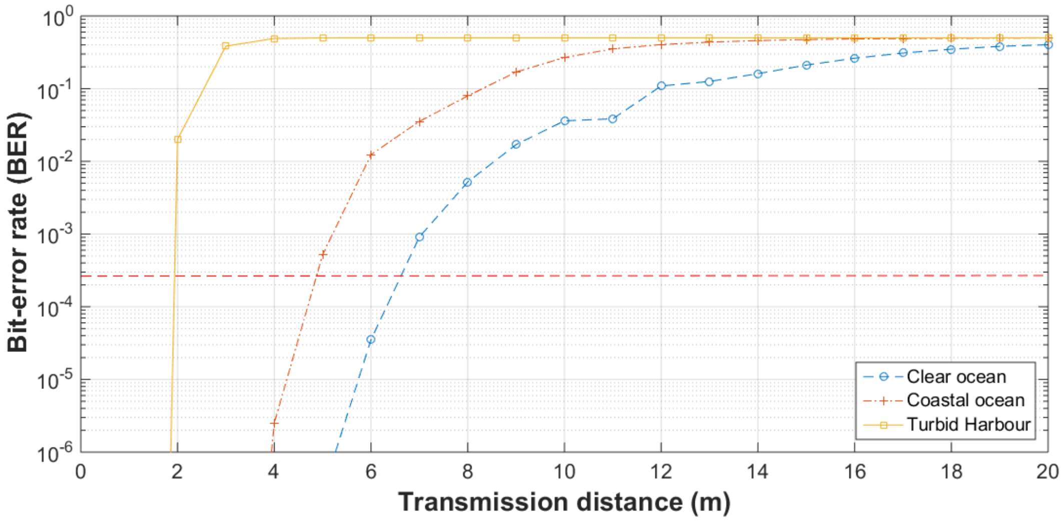

Figure 3.9 BER vs d_{Tx-Rx} for three types of natural waters

A BER of 3×10^{-3} is used as reference, as indicated by the horizontal red line in Figure 3.9. At this BER, data transmission can be made "error free" using forward-error correction with an overhead of 7% of the total data rate. Therefore, we define BERs below this level as "error free". These calculations indicate that the Fibrance transmitter concept shown here would work at a distance of almost $7m$ in clear ocean waters. This could be extended to over $10m$ if the transmitted power was increased to $50mW$. These results indicate that the Fibrance "beacon" can potentially allow a unidirectional wireless optical data link with a range of several meters, using simple components and relatively modest transmitted power.

4 Conclusions & Future Work

In this paper, it was shown that we managed to take advantage of the special property of the Corning® Fibrance® Light-Diffusing Fiber, i.e. its core scatters light continuously and uniformly, and employ the fibre itself as transmitter in clear to turbid underwater environment.

The achieved data rate (up to $5MHz$) could be increased in future measurements by employing different light sources, such as Q-Switched Laser for reaching powers up to kWs' or LEDs for more flexible and sophisticated modulation schemes (e.g. OFDM).

In future work we will explore the use of different light sources allowing selection of the optimum wavelength according to the type of water. Additional wavelengths would also be a method of increasing the transmitted data rate, or supporting multiple users, by using Wavelength Division Multiplexing (WDM).

We also intend to further investigate an "omnidirectional" transmission and more particularly, placing the receiver/detector in various positions around the Fibrance fibre allowing us to confirm the isotropic nature of the Fibrance fibre transmission. This will require trials of the Fibrance transmitter in a larger volume of water than that used here.

5 References

1. Kaushal, H. & Kaddoum, G. Underwater Optical Wireless Communication. *IEEE Access* **4,** 1518–1547 (2016).

2. Wozniak, B. *Light absorption in sea water*. (2007).

3. Wu, T.-C., Chi, Y.-C., Wang, H.-Y., Tsai, C.-T. & Lin, G.-R. Blue Laser Diode Enables Underwater Communication at 12.4 Gbps. *Sci. Rep.* **7,** 40480 (2017).

4. Doniec, M., Detweiler, C., Vasilescu, I. & Rus, D. Using optical communication for remote underwater robot operation The MIT Faculty has made this article openly available . Please share Citation Underwater Robot Operation ." IEEE / RSJ International Accessed Citable Link Detailed Terms Using Optical Comm. (2014).

5. Lanzagorta, M. *Underwater Communications*. *Synthesis Lectures on Communications* **5,** (2012).

6. Mobley, C. *Light and Water: Radiative transfer in natural waters*. (1994).

7. Johnson, L. J., Jasman, F., Green, R. J. & Leeson, M. S. Recent advances in underwater optical wireless communications. *Underw. Technol. Int. J. Soc. Underw.* **32,** 167–175

(2014).

8. Chen, Y., Kong, M., Ali, T., Wang, J., Sarwar, R., Han, J., Guo, C., Sun, B., Deng, N., and Xu, J. 26 m/5.5 Gbps air-water optical wireless communication based on an OFDM-modulated 520-nm laser diode. *Opt. Express* **25,** 14760 (2017).

9. Logunov, S., Fewkes, E., Shustack, P. & Wagner, F. Light diffusing optical fiber for Illumination. *Renew. Energy Environ. Congr.* 4–6 (2013).

10. Corning ® Fibrance ® Light-Diffusing Fiber specification sheet. 2015–2016

11. Nippon Sheet Glass Co., L. Pilkington Optiwhite. Available at: https://www.pilkington.com/en-gb/uk/products/product-categories/special-applications/pilkington-optiwhite#overview.

12. Cox, W. & Muth, J. Simulating channel losses in an underwater optical communication system. *J. Opt. Soc. Am.* **31,** 920–934 (2014).

13. Maccarone, A. *Single-photon detection techniques for underwater imaging*. (2016).

14. Hanson, F. & Radic, S. High bandwidth underwater optical communication. *Appl. Opt.* **47,** 277–283 (2008).

15. Cochenour, B., Mullen, L. & Muth, J. Effect of scattering albedo on attenuation and polarization of light underwater. *Opt. Lett.* **35,** 2088–2090 (2010).

16. Hamza, T., Khalighi, M., Bourennane, S., Pierre, L. & Opderbecke, J. On the Suitability of Employing Silicon Photomultipliers for Underwater Wireless Optical Communication Links. *10th Int. Symp. Commun. Syst. Networks Digit. Signal Process.* (2016).